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High-field electrostriction of elastomeric polymer dielectrics for actuation

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ABSTRACT

This paper investigates the use of elastomeric dielectric materials with compliant electrodes as a means of actuation. When a voltage is applied to the electrodes, the elastomeric films expand in area and compress in thickness. The strain response to applied electric fields was measured for a variety of elastomers. A nonlinear high-strain Mooney-Rivlin model was used to determine the expected strain response for a given applied field pressure. Using this model, we determined that the electrostatic forces between the free charges on the electrodes are responsible for the observed response. Silicone polymers have produced the best combination of high strain and energy density, with strains exceeding 30% and energy densities up to 0.15 MJ/m³. Based on the electrostatic model, the electromechanical coupling efficiency is over 50%. This paper also reports recent progress in making highly compliant electrodes. We have shown, for example, that gold traces fabricated in a zig-zag pattern on silicone EPAM retain their conductivity when stretched up to 80%, compared to 1–5% when fabricated as a uniform 2-dimensional electrode. Lastly, the paper presents the performance of various actuators that use EPAM materials. The technology appears to be well-suited for a variety of small-scale actuator applications.

Keywords: Electroactive polymers, artificial muscle, electrostrictive polymers, polymer actuators

1. INTRODUCTION

In many systems actuator performance is a key factor in overall system performance. In small-scale systems, such as micro robots, conventional electromagnetic technologies generally have poor performance, due to physical scaling effects and fabrication difficulties. Such small-scale systems could benefit from improved actuators. There has been much recent interest in electroactive polymers as actuator materials. In general, polymers are attractive as actuator materials because they are lightweight, easily fabricated in various shapes, low cost; and in addition their properties can often be modified as desired, by various chemical means. Within the general category of polymers, the many different possible approaches to actuators include electrostrictive polymers,¹⁻⁵ piezoelectric polymers,⁶ shape memory polymers,⁷ electrochemically actuated conducting polymers,⁸⁻¹³ polymer-based air-gap electrostatic devices,¹⁴ and so forth.

Actuators and actuator materials have several important performance parameters including energy density, specific energy density, strain, actuation pressure, response time, and efficiency. To this list must be added practical considerations such as environmental tolerance, fabrication complexity, and reliability. Given this range of performance measures, it is not surprising that different applications depend more heavily on only one or a few. Nonetheless, we consider a useful actuator technology to be one with good overall performance, as opposed to excellent performance in one or two parameters and poor performance in others. This view is supported by the dominance of electromagnetic technology on macro scales where electromagnetic actuators have good overall performance, as well as by the good overall performance of natural muscle in nature.

This paper describes an approach to electroactive polymer actuators that uses the deformation of elastomeric dielectrics. In studies of this approach since 1992, SRI has demonstrated overall performance similar to that natural muscle in many respects. Because it uses elastomers and has performance comparable to that of natural muscle, we refer to this approach as electrostrictive polymer artificial muscle (EPAM). The principle of operation is shown in Figure 1. An elastomeric polymer is sandwiched between two compliant electrodes. When a voltage difference is placed across the top and bottom electrodes, the polymer is squeezed in thickness and stretched in area. We will argue in this paper that the principal cause of this stress condition and the resultant deformation of the polymer is from the electrostatic forces of the free charges on the electrodes. It therefore is useful to introduce an analytical model that relates the observed stresses and strains to the applied voltage.

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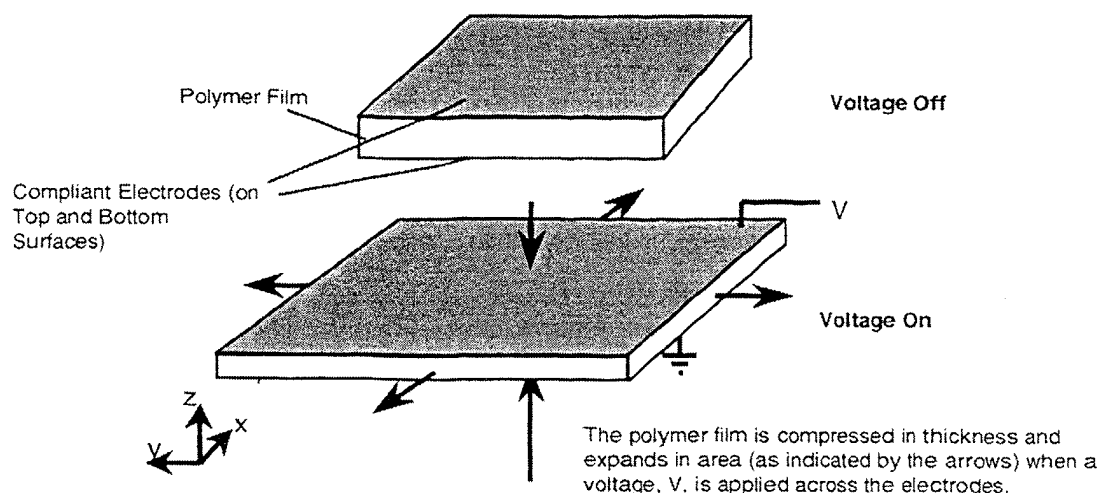


Figure 1. Principle of operation of EPAM

Derivation of the electrostatic model is described by Pelrine, Kornbluh, and Joseph.¹⁵ The actuation pressure, p , is given by

$$p = \epsilon \epsilon_0 E^2 = \epsilon \epsilon_0 (V/z)^2 \quad (1)$$

where E is the electric field, ϵ is the dielectric constant, ϵ_0 is the permittivity of free space, V is the voltage, and z is the polymer thickness. Note that this pressure is greater, by a factor of 2, than that arising from the commonly used equation for Maxwell's stress in a dielectric of a rigid plate capacitor. The greater pressure is due to the compliance of the electrodes, which allows both the forces of attraction between the oppositely charged electrodes and the forces tending to separate the charges on each electrode to couple into the effective pressure normal to the plane of the film.

For small strains with free boundary conditions, the polymer thickness strain, s_z , is given by

$$s_z = -p/Y = -\epsilon \epsilon_0 (V/z)^2/Y \quad (2)$$

where Y is the modulus of elasticity. The model for large strains with more realistic constrained boundary conditions, such as those required to drive a load, is more complex. However, this simple case illustrates the influence of the electrical and mechanical properties of the polymer on actuation performance. The model also assumes that the elastomer is an ideal rubber, that is, that the rubber is incompressible and has a Poisson's ratio of 0.5.

One of the more useful metrics for comparing actuator materials, independent of size, is the energy density of the material. The actuator energy density is the maximum mechanical energy output per cycle and per unit volume of material. For small strains with free boundary conditions, the actuator energy density, e_a , of the material can be written as

$$e_a = Y s_z^2 = (\epsilon \epsilon_0)^2 (V/z)^4/Y \quad (3)$$

Conventionally, the elastic energy density $e_e = \frac{1}{2} Y s_z^2$ is often used. However, for large strains with a linear stress-strain relation this formula must be modified because as the thickness strain becomes increasingly negative, the film flattens out and the area over which the pressure must be applied increases. A more detailed derivation for large strains gives the formula for the elastic energy density of materials with a linear stress-strain relation as

$$e_e = Y [(s_z - \ln(1 + s_z))] \quad (4)$$

This equation agrees with the more common formula at small strains but is significantly higher for strains greater than 20%.

Various electrostrictive mechanisms can be considered for polymer actuators. While the mechanism for EPAM relies on electrostatic forces, the performance of an EPAM actuator is critically determined by the electrical and mechanical properties of the polymer. In particular, EPAM performance depends on the macroscopic permittivity of the polymer as well as on its modulus of elasticity. Therefore, it is appropriate to consider EPAM as an electrostrictive polymer technology for the purposes of this study.

2. EXPERIMENTAL PROCEDURE FOR MEASURING MATERIAL PERFORMANCE

The experiments in our study were designed to measure the response of different polymer materials to applied electric fields. The purpose of the experiments was to identify the most promising polymers, compare the polymer actuator's performance to that of other actuator technologies, and determine the validity of our electrostatic model of actuation.

The measurement of the performance of different polymer materials is complicated by the fact that several of the polymer materials evaluated are relatively soft (have elastic moduli below 1 MPa). Therefore, the constraints on the polymer film must be carefully controlled. The situation is further complicated by the fact that film samples are often quite thin. We therefore used optical methods to measure the strain condition of the polymer film.

The measurement configuration is shown in Figure 2. A thin film of a polymer is stretched uniformly across a circular hole in a rigid frame. Electrodes are applied to a relatively small circular area at the center of this frame. When a voltage is applied to the electrodes, the film between the electrodes expands in area and contracts in thickness. This expansion in area is measured with an optical microscope, a video camera, video digitizing hardware, and digital measurement software. The software measures the amount of motion of identifiable features on the surface of the electrodes (such as texture features) when a voltage is applied. By comparing the location of the features at a given voltage to the locations at zero voltage, we determine the in-plane strain at a given voltage. The magnification of the microscope and resolution of the video camera are such that a single pixel represents only a small portion of the observed motion. Most measured motions were on the order of tens of pixels. Photographs of one such experiment with Dow Corning HS3⁺ silicone are shown in Figure 3.

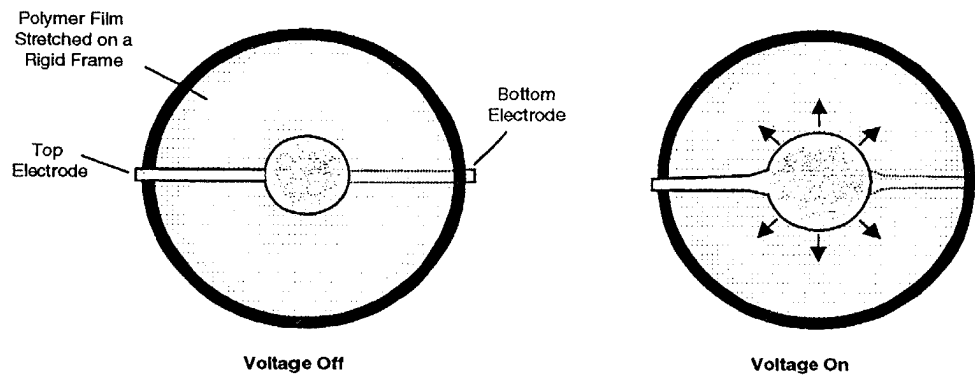


Figure 2. Experimental setup (top view)

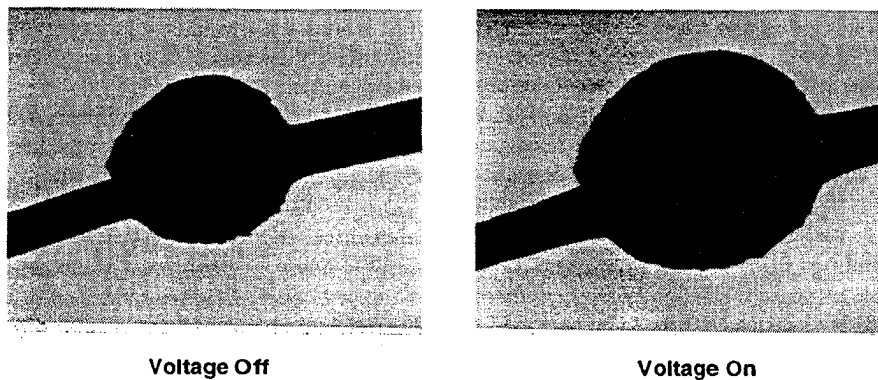


Figure 3. Experimental results: HS3 silicone showing approximately 68% area strain (41% thickness strain)

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The effects of creep and mechanical hysteresis on the measured strain were minimized by obtaining the strain reading immediately following the application of the voltage. The voltage was brought to zero between each measurement. Any effects of electrical hysteresis on the strain measurement were assumed to be insignificant compared to the total measured strain.

Films of the polymers were prepared by dissolving the uncured polymer in a suitable solvent, such as naphtha for the silicone rubbers (polydimethyl siloxane). The polymer solution was then spun onto a disk at a speed appropriate to give a thin uniform coating. This operation was performed in a clean room to minimize the introduction of particulates into the film. The sample was then allowed to dry, to remove the solvent. Certain polymers were further cured at elevated temperatures according to the manufacturers' specifications for a complete cure. Film samples varied from 1 to 100 μm in thickness, depending on the properties of the film. In general, film thickness was chosen to give a maximum sustainable voltage between 1 and 10 kV.

The selection of electrode materials is an area of ongoing research and is discussed in Section 6. For our measurements we wanted a thin, extremely low-modulus electrode that provided uniform charge distribution over the surface of the film under the electrodes. In most cases, ultrafine graphite powder and carbon blacks were brushed onto the surface of the film through a stencil. For many of the silicones that are capable of undergoing extremely large strains, it was necessary to coat these electrodes with a mixture of silicone-polymer-based graphite grease and carbon-filled silicone (Chemtronics CW720 and Stockwell RTV 60-CON, respectively) in order to ensure full coverage at large strains.

Measurement of the strains can serve as a basis of comparison between different polymers. For actuator design however, it is most useful to compare materials on the basis of energy density, since some materials may be capable of higher strains and others capable of higher pressures. Additionally, elastic energy density is typically used as a means of comparison between different actuator materials. In order to determine the elastic energy density of the material from the measured strain, it is necessary to characterize the elastic properties of the polymers and accurately model the constraints of the experimental setup. Another motivation for modeling the mechanical pressures from the measured strains is that we can compare our measured polymer performance with that suggested by the electrostatic model described in Equation 1. The verification of this model has important implications for material selection and actuator design.

The tensile elastic modulus was obtained by measuring the force on a thin strip of polymer material at different linear strains. The compressive modulus was assumed to be equal to the tensile modulus.

The constraints of the experimental setup may be considered analytically due to the high degree of symmetry of the setup. However, the highly nonlinear nature of the elastic behavior of most polymers and the large strains make the analysis more difficult. A finite element analysis with a Mooney-Rivlin material model was used to account for both of these effects.^{16, 17}

3. EPAM MATERIAL PERFORMANCE

As seen from Equations 1-3, the ideal EPAM material, with maximal energy density, has a high dielectric constant ϵ , a high breakdown strength (V/z), and a low modulus of elasticity Y . For most applications, desirable material properties also include low viscoelastic losses, a wide range of temperature and humidity tolerance, and ease of fabricating thin films. Table 1 shows the measured performance of some of the polymers we have tested.

In this table, strain, electric field, modulus, and dielectric constant are measured. The pressure and elastic energy density are estimated via factors derived from the nonlinear finite element model of the film, together with the measured strain. The coupling efficiency, k^2 , deserves some comment. The square of k is used for consistency with the conventional nomenclature for piezoelectrics. The electromechanical coupling factor is defined as follows:

$$k^2 = \text{energy converted into mechanical work per cycle/electrical energy applied per cycle.}$$

Electromechanical coupling efficiency is an important parameter for many applications. Materials with low coupling efficiencies are difficult to operate efficiently even if there is no intrinsic energy loss mechanism, because low coupling requires a large amount of electrical energy to be removed or recovered from the actuator relative to the work output. Even with high-efficiency recovery (e.g., 90% efficient) circuits, if the coupling is too low, too much energy is lost in the recovery electronics, relative to the work output per cycle.

Table 1. Maximum response of representative elastomers

Polymer (Specific type)	Elastic Energy Density (J/cm ³)	Pressure (MPa)	Strain (%)	Young's Modulus (MPa)	Electric Field (V/μm)	Dielectric Constant (@1 kHz)	Coupling Efficiency, <i>k</i> ² (%)
Silicone Nusil CF19-2186	0.15	0.72	32	1.0	235	2.8	54
Silicone Dow Corning HS3 (centrifuged to remove particulates)	0.038	.13	41	0.125	72	2.8	65
Polyurethane Deerfield PT6100S	0.20	3.8	11	17	160	7.0	21
Silicone Dow Corning Sylgard 186	0.10	0.50	32	0.7	144	2.8	54
Fluorosilicone Dow Corning 730 (centrifuged to remove particulates)	0.051	0.29	28	0.5	80	6.9	48
Fluoroelastomer LaurenL143HC	0.016	0.39	8	2.5	32	12.7	15
Polybutadiene Aldrich PBD	0.025	0.41	12	1.7	76	4.0	22
Isoprene Natural Rubber Latex	0.010	0.19	11	0.85	67	2.7	21

Average engineering modulus at the maximum strain.

Coupling efficiency is often difficult to measure directly, but we can use the electrostatic model (in which the permittivity of the material does not change) to estimate the EPAM coupling efficiency, based on the capacitance change for the given strain. That is, the capacitance, *C*, varies as

$$C = \epsilon \epsilon_0 A/z = \epsilon \epsilon_0 U/z^2 \quad (5)$$

where *U* is the total volume of the material. Note that the last equality uses the constant volume property of elastomers, i.e., *Az* = *U* is approximately constant throughout the actuation. Using Equation 5 with a constant charge drive gives the percentage change in electrical energy at the assumed strain, starting at State 1 and actuating to State 2, as follows.

$$\begin{aligned} \Delta E/E_1 &= (E_2 - E_1)/E_1 = ((Q^2/C_2) - (Q^2/C_1))/(Q^2/C_1) \\ &= (z_2^2 - z_1^2)/z_1^2 = 2 s_2 + s_2^2 \end{aligned} \quad (6)$$

where we have used *z*₂ = *z*₁ (1 + *s*₂). Our best EPAM polymers typically have low viscoelastic losses, so that the change in electrical energy is approximately equal to the work output, taking into account a minus sign (*s*₂ < 0), i.e.,

$$k^2 = -2 s_2 - s_2^2 \quad (7)$$

Equation 7 is an approximation but indicates that EPAM materials with a strain of 32% can have a coupling efficiency up to approximately *k*² = 54% (*k* = 0.73), a competitive value compared to piezoelectric materials and other field-actuated actuator technologies.

Finally, we note that analysis indicates that strains of around 33% would be the maximum achievable strains under DC test conditions with linear materials.¹⁵ As the polymer contracts in thickness, with a constant voltage the electric field pressure increases. Beyond 33% thickness strain, the material undergoes an electromechanical instability and locally contracts rapidly in thickness until breakdown occurs. This phenomena is similar to "pull-in" instabilities (e.g., as reported by Gupta and Senturia¹⁸) in conventional, air-gap electrostatic actuators. We have not absolutely confirmed that electromechanical instability limits EPAM performance, but the fact that a number of materials with very different elastic moduli have peak strains in the range 25–35% suggests that such instability may be a limiting factor.

It is important to note that the 33% strain instability is subject to a number of qualifications that may allow higher performance to be achieved. In particular, the 33% strain value does not apply to polymers having nonlinear moduli of

elasticity (as all polymers do to some extent), nor does it apply to actuators where part of the strain is caused by dynamic or static loading constraints. Indeed, the peak 41% thickness strain we have measured using HS3 silicone indicates the 33% "limit" is not fundamental but is rather a practical limitation that may apply to some materials under certain loading conditions.

Nusil CF19-2186 silicone rubber has amongst the highest measured energy density and strains of known EPAM materials. Other materials such as polyurethane can achieve higher actuation pressures at lower voltages, due to their greater permittivity (the dielectric constant of polyurethane is roughly 7, compared to 3 for silicones). However, silicone has better coupling efficiency as well as other properties, including low creep and excellent tolerance to temperatures and humidity, that make it more attractive as an for many actuator applications. Consequently, most of our actuator development has focused on the use of silicones.

4. VALIDATION OF ELECTROSTATIC MODEL

The measured strain of a silicone rubber film (Dow Corning HS3) as a function of the applied electric field is shown in Figure 3. This strain is compared to that which would be expected based on the pressure from the electrostatic mode described by Equation (1). As can be seen, there is very close agreement between the measured strain and that predicted by the model. Although the HS3 silicone provides the best fit, we have not seen any compelling evidence from tests with any of the polymers that would suggest the action of a mechanism of electrostriction other than that arising from the electrostatic forces enhanced by the polymers' dielectric constant. This result is not surprising, since we have focused our attention on soft elastomers, which tend to have noncrystalline amorphous molecular structures. These structures would not be expected to be much influenced (beyond ordinary polarization) by the application of electric fields. We do not claim, however, that there is no such inherent electrostrictive response, only that it is small compared to that of the electrostatic forces under the conditions tested.

Also shown in Figure 4 is a curve of the strain that would be expected from a test sample with free boundary conditions. This curve illustrates the importance of accurately modeling the constraint conditions. The curve also suggests that actuators with different constraints might be able to undergo greater strains than the constrained sample films.

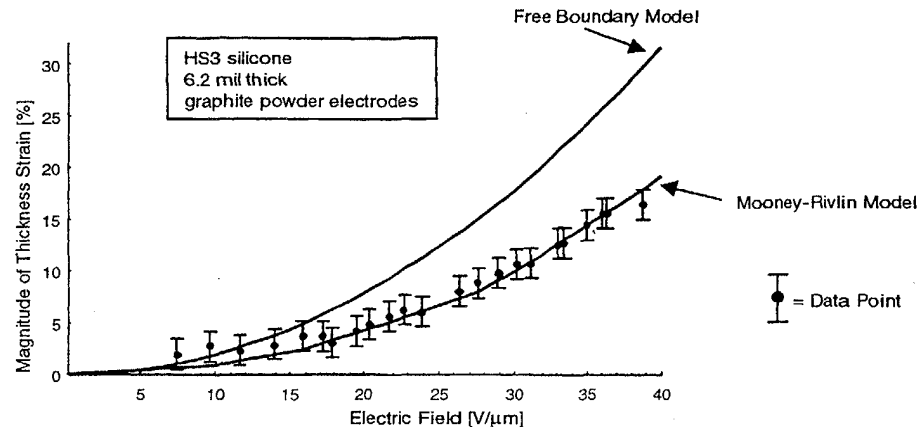


Figure 4. Response of silicone rubber to an electric field; comparison with electrostatic model

5. COMPARISON TO COMPETITIVE TECHNOLOGIES

Table 2 shows several characteristics of EPAM materials and other electric actuation technologies, including several electroactive polymer technologies.

As can be seen in Table 1, EPAM is not the best technology in any single measure of performance. However, its overall performance is encouraging enough to suggest that it can be used competitively in energy-efficient actuators that are lightweight and compact relative to common actuation technologies such as electromagnetics and piezoelectrics.

Table 2. Comparison of EPAM to other actuator technologies

Actuator Type (specific example)	Maximum Strain (%)	Maximum Pressure (Mpa)	Specific Elastic Energy Density (J/g)	Elastic Energy Density (J/cm ³)	Coupling Efficiency k' (%)	Maximum Efficiency (%)	Specific Density	Relative Speed (full cycle)
Electrostrictive Polymer Artificial Muscle								
Silicone	32	0.72	0.15	0.15	54	90	1	Fast
Polyurethane	11	3.8	0.20	0.20	21	80	1.1	Fast
Electrostrictor Polymer (P(VDF-TrFE)) ³	4	15	0.17	0.3	5.5	-	1.8	Fast
Electrostatic Devices (Integrated Force Array) ²	50	0.03	0.0015	0.0015	50 (est.)	>90	1	Fast
Electromagnetic (Voice Coil)	50	0.10	0.003	0.025	n.a.	>90	8	Fast
Piezoelectric								
Ceramic (PZT) [†]	0.2	110	0.013	0.10	52	>90	7.7	Fast
Single Crystal (PZN-PT) ²⁰	1.7	131	0.13	1.0	81	>90	7.7	Fast
Polymer(PVDF) ^{‡26}	0.1	4.8	0.0013	0.0024	7	-	1.8	Fast
Shape Memory Alloy (TiNi) ²¹	>5	>200	>15	>100	5	<10	6.5	Slow
Shape Memory Polymer (Polyurethane) ⁷	100	4	2	2	-	<10	1	Slow
Thermal (Expansion) ^{**}	1	78	0.15	0.4	-	<10	2.7	Slow
Electrochemo-mechanical Conducting Polymer (Polyaniline) ⁸	10	450	23	23	<1	<1%	-1	Slow
Mechano-chemical Polymer/Gels (polyelectrolyte) ²²	>40	0.3	0.06	0.06	-	30	-1	Slow
Magnetostrictive (Terfenol-D, Etrema Products) ²⁷	0.2	70	0.0027	0.025	-	60	9	Fast
Natural Muscle (Human Skeletal) ²²	>40	0.35	0.07	0.07	n.a.	>35	1	Med

*These values are based on an array of 0.01 m thick voice coils, 50% conductor, 50% permanent magnet, 1 T magnetic field, resistivity of 2 ohm-cm, and 40,000 W/m² power dissipation.

[†]PZT B, at maximum electric field of 4 V/μm. ¹⁹

[‡]PVDF, at maximum electric field of 30 V/μm. ²⁶

**Aluminum, using a temperature change of 500°C.

EPAM does have one notable characteristic that may be considered a disadvantage in certain applications. In general, EPAM operates at relatively high voltage (e.g., typically as high as 100–4000 V, depending on material thickness and properties). This high voltage adds greater complexity to the electronics electromagnetic and other low voltage drives. However, we note that voltage amplifiers can be made quite small (e.g., we have demonstrated 4 X high-voltage multipliers with roughly 5 mm³ of components) so the disadvantage is not fundamental, but rather an issue of developing suitable ICs and components with the desired voltage and power ratings. High-voltage operation can be an advantage in some applications, since it allows for more efficient transmission of the electrical energy through thin wires and less-than-perfect connectors.

One other potential disadvantage is that EPAM is intrinsically a variable capacitive drive. After actuation, capacitive electrical energy remains on the actuator. In this respect EPAM is similar to piezoelectric and conventional, air gap electrostatic actuators. For maximum efficiency, energy recovery circuits are needed. Within the class of actuators that require energy recovery circuits, however, EPAM is particularly attractive because of its high electromechanical coupling (discussed in Section 3).

6. EPAM FABRICATION ISSUES

EPAM technology can borrow many techniques and materials from the microelectronics and MEMS communities. The materials used are relatively low cost and commercially available. However, many features of the technology require unique materials and actuator designs.

EPAM films can be made by casting, dipping, spin coating, or spraying. Spin coating generally yields the best-performing films because the spin coating process is able to fabricate films of high uniformity. Spin coating is also the preferred process for the thinnest films: we have demonstrated the fabrication of 1- μm -thick silicone EPAM films. The fabrication procedure for making spin-coated actuator films is the same as that for the polymer samples described above.

A key feature of EPAM technology is the use of compliant electrodes. If the electrodes cannot stretch in at least one planar direction of the film while its thickness contracts, actuation will be dramatically reduced because the polymer is essentially incompressible, i.e., its bulk modulus is much greater than its elastic modulus. Fortunately, for energy efficient operation the compliant electrodes need not be very conductive, due to the high-voltage, low-current drive typical of electrostatic devices.

As noted above, the selection of electrode materials remains an ongoing area of research. The more successful materials have typically been based on small particles of carbon: for example, powdered graphite, carbon black, and carbon grease. These materials can be deposited directly on the film in a screen-printing process, or they can be sprayed on the film with a fast-evaporating carrier liquid.

Carbon-based electrode materials work reasonably well but have drawbacks. In particular, it is difficult to get a smooth, uniform electrode from carbon particles. This is not an issue for single-layer actuators, or for multilayer actuators that are mechanically assembled from single-layer films. However, ideally one would like to be able to fabricate multiple layers of EPAM in situ. To do this, however, one needs an extremely smooth electrode to prevent local thinning of the elastomer deposited on top of the electrode.

One approach is to use sputter-deposited, ultrathin gold with thicknesses below 0.1 μm , for compliant electrodes. Unfortunately, uniform gold electrodes easily crack, and strains greater than about 4% are difficult to achieve with this technique. Recently, we have demonstrated that patterned, rather than uniform gold electrodes can remain conductive at much greater film strains. Zig-zag patterns of gold traces deposited on silicone EPAM, such as those shown in Figure 5, remain highly conductive at film strains up to 80%. The gold traces are sputtered uniformly on the film, then patterned via photolithography. Photolithography on soft polymers has not been reported in the literature; therefore it was necessary to refine the processes. We have successfully fabricated gold traces with line widths as small as 5 μm .

The zig-zag traces carry charge out onto the film, but a second electrode material is needed to carry the charge in between the zig-zag traces, for uniform distribution over the surface of the polymer. Fortunately, this problem is easy to address, because the resistivity of the second electrode material can be quite high. For a 50- μm -thick silicone film with 500- μm trace spacing, for example, the surface resistivity to achieve a 100 Hz response can be as high as 10^{10} – 10^{11} ohms per square (based on the RC time constant of the film). Indeed, we have shown that even air is sufficiently conductive to carry charge between finely spaced metal traces. By contrast, the maximum surface resistivity of a uniform electrode (without gold traces) for a 10 cm^2 piece of film of the same thickness is about 4000 times lower for the same 100 Hz response.

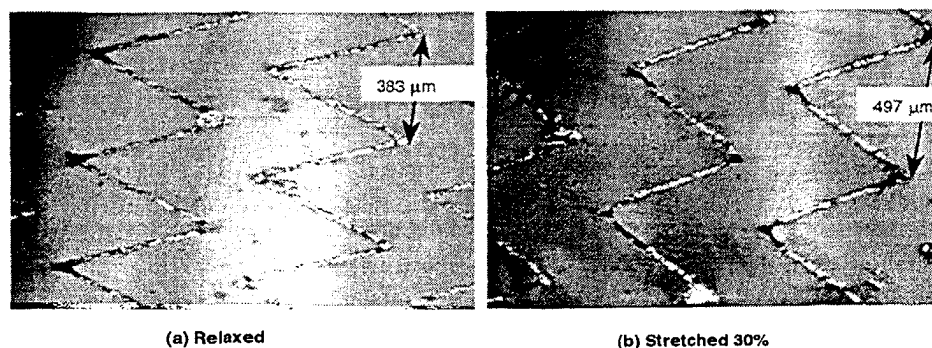


Figure 5. Zig-zag gold electrodes undergoing large strains

The use of electrodes having two different conductivities can improve reliability and robustness. The electrode materials can be configured as *structured electrodes*, as illustrated in Figure 6. Note that with structured electrodes, no matter where a breakdown occurs, the electrical breakdown current must pass through the low-conductivity material before it can reach a high-conductivity trace. The low-conductivity material thus limits breakdown current and localizes the breakdown effects to prevent catastrophic failure. The low-conductivity material also limits leakage current and helps maintain efficiency even in the presence of breakdowns. For example, with a surface conductivity of 10^{11} ohm per square, even with an operating voltage of 1000 V the power loss from a breakdown is only 10 microwatts, a negligible amount for most applications.

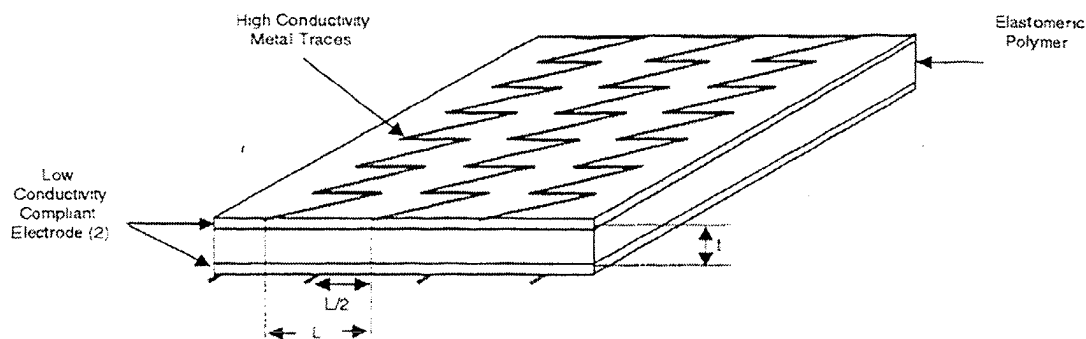


Figure 6. Structured electrodes

Another way to limit breakdowns is to use self-healing electrodes. Self-healing electrodes are well known in the manufacturing of certain types of capacitors. However, capacitors do not stretch, and therefore the choice of electrodes is less restricted. We have demonstrated self-healing electrodes using gold, conductive polymers, and carbon-based electrodes. Promising conducting polymer electrodes have focused on solvent-based solutions of doped polyaniline, although numerous ionically conductive materials have also been evaluated. The self-healing property is less dependent on the material than it is on the electrode and film thicknesses. This observation is not surprising, since self-healing generally works by locally vaporizing the electrode material during breakdown. Thus, electrode materials can usually be made self-healing if they can be used in sufficiently thin layers. Unfortunately, most of the self-healing electrode materials capable of undergoing large strains (such as conducting polymers) have not shown good long-term performance on silicone. One possible reason for this poor performance appears to be the poor adhesion of the polymer to the silicone. Another possible explanation is that the film area in the vicinity of the electrode defect experiences both an electric field concentration and a stress concentration. These factors combine to allow the defect to propagate from the initial location. The development of self-healing electrodes remains an area of active research.

7. EPAM ACTUATORS AND ACTUATOR DESIGN

A wide variety of EPAM actuator configurations have been demonstrated. Several are analogous to well-known piezoelectric configurations. Others take advantage of the unique capabilities of high-strain polymer actuators. Here we briefly describe three such actuators that illustrate the range of possible designs.

7.1. Unimorph and Bimorph Actuators

Unimorph and bimorph actuators are similar to their piezoelectric counterparts and work well with EPAM materials. Applications for unimorph and bimorph EPAM actuators include oscillating micro fans, displays, and low force robotic elements such as grippers. Strains are higher with EPAM than with competing piezoelectric materials, so higher bending angles can be achieved with shorter devices and without resorting to submicron film thicknesses. Bending angles approaching 360° have been achieved with 5-mm long unimorphs. Figure 7 shows a photo of an EPAM unimorph made from silicone. The electrodes are sputtered gold on the bonded surface and carbon black on the free surface. The sputtered

gold is sufficiently stiff, compared to the silicone, that the strain is much less at the gold electrode than the carbon black electrode. The result is that the film bends toward the carbon black electrode when a voltage is applied.



Figure 7. EPAM Unimorph undergoing actuation

One point to note with EPAM bimorphs is that with suitable construction they can have an additional extension degree of freedom, as illustrated in Figure 8. In principle, piezoelectric materials can also implement this configuration; however, the extension strain with piezoelectrics is usually much smaller than the typical bending motion than it is of limited use.

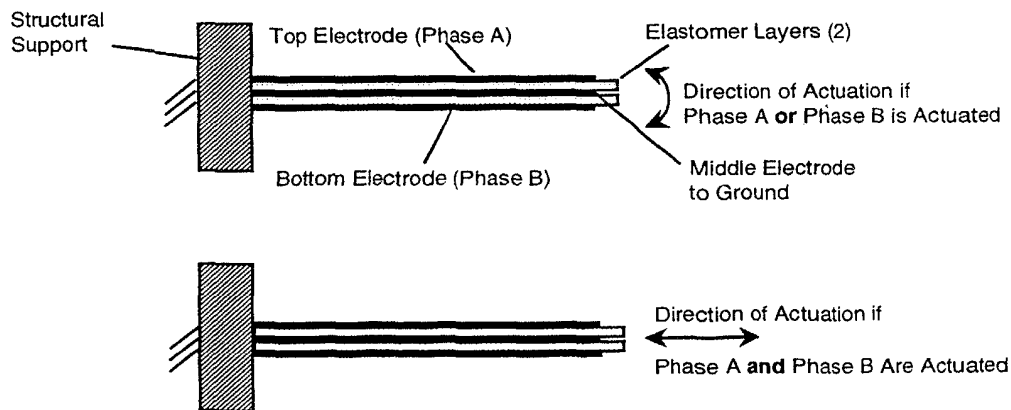


Figure 8. EPAM bimorph construction for 2 degrees of freedom

7.2. Rolled Actuators

Unlike piezoelectric ceramics, EPAM film can be rolled up to form a linear rolled actuator, as illustrated in Figure 9. Since it is easiest to fabricate and deposit electrodes on a single flat layer of film, rolled actuators are an easy way to squeeze a large single layer of film into a compact shape. Rolled EPAM actuators are potentially applicable wherever linear actuators are used, such as robotic legs and fingers, high-force grippers, and general-purpose linear actuators (e.g.,

wherever electromagnetic solenoids or voice coils are used). Rolled EPAM actuators have been used for most EPAM reliability tests to date; for example, an actuator of this type was demonstrated for more than 10,000,000 cycles without significant performance degradation. Rolled actuators have been fabricated that have maximum strokes of 5–7% of their active lengths. Larger rolls with forces ranging up to nearly 1 N also have been demonstrated.

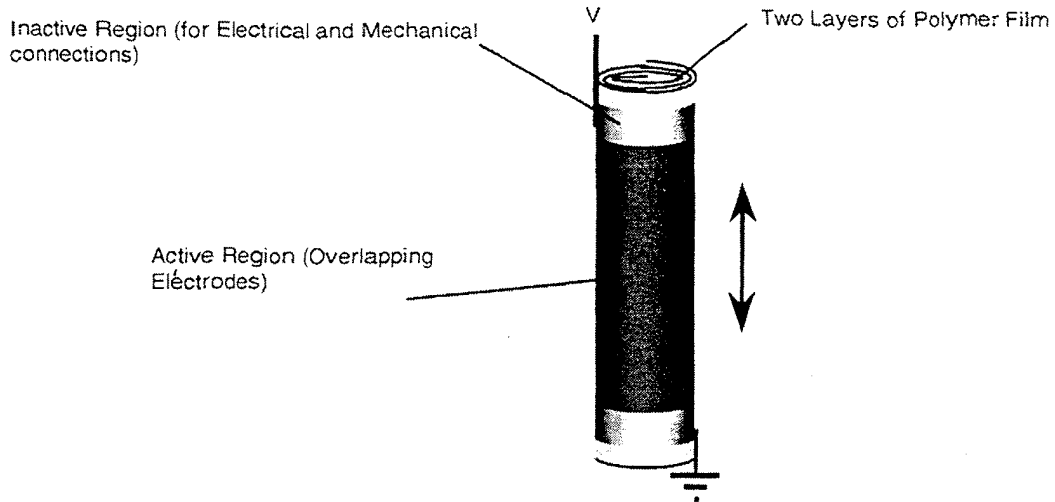


Figure 9. Rolled EPAM actuator

7.3. Diaphragm Actuators

Diaphragm EPAM actuators work very well, in part because a diaphragm can easily exploit both directions of planar expansion of the film. Figure 10 illustrates an EPAM diaphragm actuator. Diaphragms are particularly well suited for pumps but could also be used for adaptive optics, loudspeakers,²³ or controllable surface roughness (e.g., on an aerodynamic surface). For pumps, single EPAM diaphragm actuators with up to 20 kPa (3 psi) pressure with 3-mm-diameter diaphragms have been demonstrated. Multiple cascaded pumps could be used to increase pressure, or thicker diaphragms could be used. An attractive feature of EPAM diaphragms as opposed to competitive piezoelectric diaphragms is that the displacement can be relatively large without sacrificing other performance parameters. Diaphragm motion with EPAM can easily be 10% or more of diaphragm diameter. Large diaphragm motions are possible in principle using piezoelectrics, but because the intrinsic strain of piezoelectrics is so much smaller than with EPAM, only very thin piezoelectric diaphragms could achieve similar strokes. The use of very thin diaphragms, however, sacrifices other parameters such as pumping pressure or packaging density, and in most cases significantly reduce the size of piezoelectric diaphragm strokes.²⁴

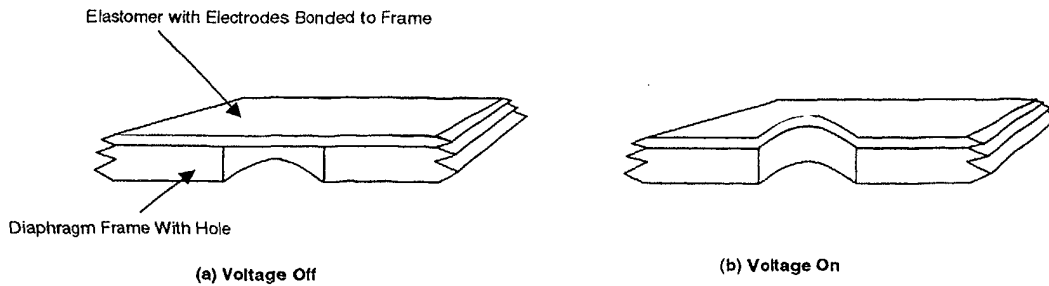


Figure 10. Schematic of a diaphragm actuator (cross-sectional view)

8. SUMMARY AND CONCLUSIONS

Elastomeric polymers show promise as actuator materials when employed as a dielectric between compliant electrodes. EPAM materials show excellent overall performance and appear more attractive than many competitive actuator technologies. Strains over 30%, actuation pressures of 0.7 MPa, and energy densities of 0.15 J/cc have been demonstrated with silicone rubbers. Response time is rapid, and the potential efficiency is high.

Experimental measurements of strain in a variety of elastomeric materials have validated the electrostatic model of electrostriction. Mooney-Rivlin finite element modeling, which can address large strains and elastic nonlinearities, was used to help validate the model. We plan to extend this modeling technique beyond fundamental measurements of stress and strain to actuator design.

The key technical issues for EPAM technology include the selection of elastomer materials and compliant electrode materials, the fabrication of integrated elastomer-electrode structures, material modeling, and actuator design. Improved elastomer materials are an ongoing area of research, though current performance is already attractive for many applications. Compliant electrodes have been based primarily on carbon particle materials (e.g., graphite, carbon black), but structured electrode approaches using, for example, patterned zig-zag gold traces in conjunction with a low conductivity material may be more promising in the long term. Excellent quality single layer elastomer films can be fabricated via spin coating. In the fabrication area, some progress has been made in demonstrating in-situ multilayer fabrication, but at present the performance of these films is inferior to that of single layer fabrication. A variety of EPAM actuators have been fabricated and demonstrated with good performance. These actuators have many potential applications for pumps, robots, and general-purpose linear actuators. Their large strain capabilities suggest that these linear actuators could be used for muscle-like actuation in small robots.

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